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Chemical Time-Series Sampling

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16. ABSTRACT The rationale for chemical time-series sampling has its roots in the same fundamental relationships as govern well hydraulics. Samples of ground water are collected as a function of increasing time of pumpage. The most efficient pattern of collection consists of logarithmically spaced sampling intervals, analagous to the collection of drawdown data during pumping tests. The analogy extends further because simultaneous collection of drawdown values, flow rates, and chemical time-series samples yields a set of data which can be used to determine not only the distance from which specific levels of contaminants were drawn, but also the direction from whence they came.

The potential power of this technique in locating contaminant sources is obvious and is enhanced by analysis of the patterns of concentrations of contaminants drawn into the well. Further implications of the method include the ability of the user to clearly define minimum purging requirements and sampling radii of monitoring wells, and the need for sampling by methods which create an appreciable local gradient toward the well. This technique also indicates the noncomparability of data collected by grab sampling wells of different flow rates, pumping durations, and/or construction.

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CHEMICAL TIME-SERIES SAMPLING

A technique which collects successive pumped samples from one discharging well is described and analyzed.

by Joseph F. Keely

Commonly employed methods of ground-water quality assessment (involve collection of point samples) particularly where contamination is suspected. Bailers or other low volume sampling devices are used to obtain samples from fairly small diameter monitoring wells (Scalf and others 1981). Generally, economic constraints are cited as the primary reason for using only a few monitoring wells to attempt to define rather complex contaminant distributions in the subsurface environment.

Most ground-water professionals recognize the severe limitations of data gathered in such a fashion; questions about "how representative of true aquifer quality such samples are" occupy a great deal of the time and effort expended on ground-water contamination investigations. The remedies suggested to answer these questions usually fall into the areas of greater numbers and specific locations of additional monitoring wells.

It is possible, however, to gain more information with fewer wells by collecting dynamic samples. That is, discharging wells can be sampled as a function of the time since pumping began (chemical time-series sampling). Each successive pumped sample represents ground water from a part of the aquifer farther from the well than the samples obtained before it. In this sense, the overall effect is equivalent to increasing the number of point-sampled monitoring wells. However, tremendous gains in efficiency and economy are also realized by sampling in this manner because hundreds or thousands of point-sampled wells would be required to sample the same volume of aquifer as is sampled by a single pumping well, after only a short period of pumping.

Perhaps more importantly, the patterns of arrivals of contaminants as a function of pumpage can be examined to yield insights into the locations of contaminant sources and plumes—much as injection-withdrawal tracer tests are used to determine preferential avenues of flow. Nearby monitoring wells that lie within the cone of pumping influence become useful for chemical time-series sampling too, analogous to observation wells for drawdown measurements during aquifer tests. Further analogies to traditional geohydraulic testing are evident. Just as the effects of hydraulic boundaries can be seen in such tests, artificial hydraulic boundaries can be created by causing the cones of influence of adjacent pumping wells to overlap. Contaminant sources and plumes can be effectively isolated by these boundaries so that contaminants are primarily drawn into only one pumping well and are available only to monitoring wells on the same side of the hydraulic boundary as the contaminant source or plume.

This article pursues these topics in depth. Simple hypothetical examples are examined for illustrative purposes; further field applications will be described elsewhere in the literature (Keely, in progress).

Mechanics of Time-Series Sampling

The mechanics of chemical time-series sampling are as follows:

- The wells to be sampled must not have been disturbed (e.g., not pumped) for several hours to several days prior to testing. Nearby discharge wells need not be inoperative, but must remain at constant pumping rates and these rates must be known. This allows the aquifer to attain a steady-state configuration locally.
- The static water levels of each well are measured just prior to the onset of pumping. "Zero time" ground-water samples are then taken with bailers. These samples represent relatively stagnant waters residing in the well casing—but will be important for interpretive purposes.
- A pump in one of the wells to be tested is started and chemical samples and water level measurements are taken at logarithmically spaced intervals: e.g., 1, 5, 10, 30, 60, 180 and 300 minutes since pumping started. Samples and drawdown measurements are also taken at similar times in nearby non-pumping wells. Logarithmically spaced intervals for chemical sampling are most efficient because the time required for arrival of withdrawn waters increases considerably as one gets farther and farther away from the well. The distance from which contaminants were drawn is directly related to the total volume of water drawn by the well since pumping began, which in turn is dependent on a power function—the square of the distance from the well.
- Just after the last samples and measurements are taken, a second pumping well is started—*without* shutting off the first well. The two wells will compete for waters lying

within their mutually overlapping cones of depression. The artificial ground-water divide, separating waters drawn into each well, will potentially result in isolation of the contaminant(s) on one side of the divide. Such an effect was recently noted by the author in an investigation of two Lakewood, Washington, public water supply wells contaminated with tetrachloroethylene, trichloroethylene and other volatile organics. The contaminants had been routinely detected in one of the wells until the other began pumping, at which point the contaminant levels in the first well rapidly declined to near non-detectable levels. Figure 1 illustrates this mechanism of contaminant isolation. Samples and drawdown measurements are taken several times (e.g., 5, 30, 60, 180 and 300 minutes) at each monitoring and pumping well following the onset of pumpage at successive wells. The test is then terminated by shutting off all wells and recording recovery levels.

Note that contaminant arrival effects are not limited to the pumping wells, since local displacement of waters caused by pumping wells will be observed in nearby monitoring wells.

The emphasis on concurrent drawdown measurements for estimation of aquifer transmissivity and storage values are of paramount importance; each monitoring well near the pumping well(s) will yield estimates specifically influenced by aquifer characteristics in that direction.

The collection of such data will enable the investigator to map zones of high transmissivity, such as buried stream channels or glacial outwash gravels, and zones of low transmissivity, such as clay lenses and tight silts. Similarly, zones of semiconfining or fully confined aquifer waters, somewhat protected from the downward percolation of surface waters and contaminants, can also be effectively mapped.

Patterns of Contaminant Arrival

Some of the patterns of contaminant arrival which might result from time-series sampling are illustrated in Figure 2. Patterns I through IV (Figure 2) portray variations on trends of decreasing concentrations with continued pumpage. No attempt will be made here to detail the litany of potential interpretations for each pattern illustrated in Figure 2, but some of the more likely possibilities follow.

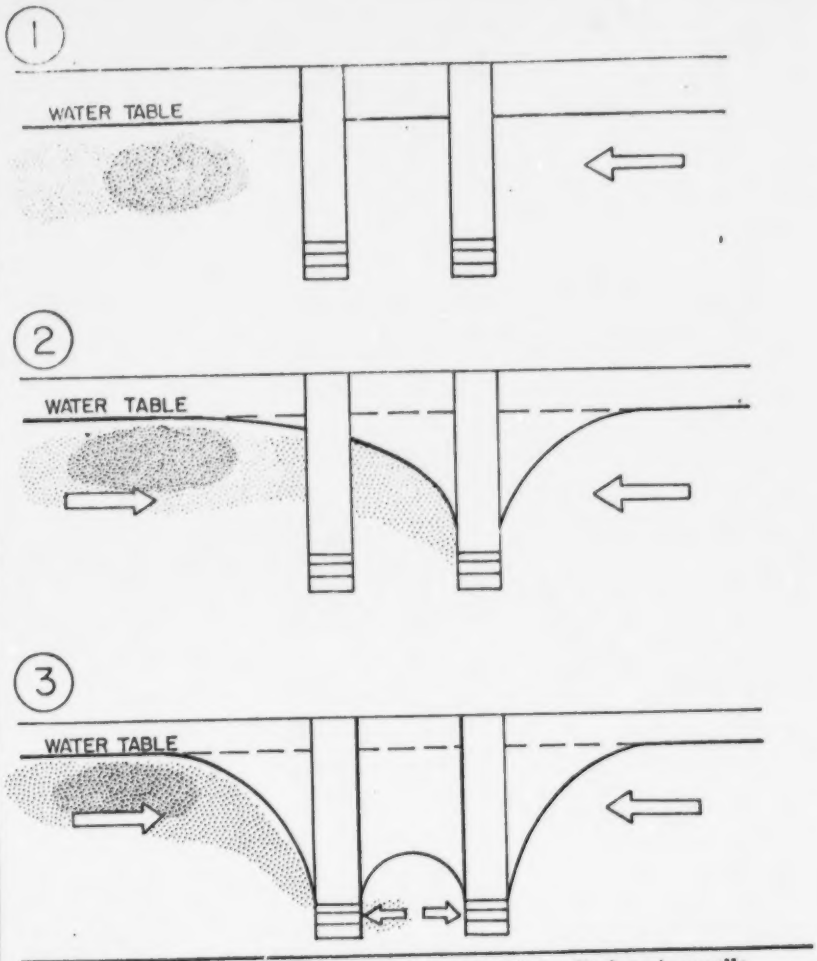

Figure 1. Sampling and isolation of contaminants by discharging wells

Pattern I might result from placing the well so that it penetrates a contaminant plume of very limited extent; contaminant levels decrease due to an increase in the availability of uncontaminated aquifer waters as the distance from which the waters were drawn into the well becomes greater and greater. It might also be that the well penetrates a substantial plume, but is located close to one edge of the plume. Or it might be that a slow, but steadily increasing contribution of additional uncontaminated waters, such as from upconing or from leaky confined beds, is gradually reducing the ratio of contaminated-to-uncontaminated aquifer waters drawn into the well. Each hypothesis could be strengthened or challenged by supplemental data; e.g., if pumping tests show the existence of leaky artesian conditions locally, the last hypothesis may be most supportable. If nearby wells are unable to penetrate the same plume, the first hypothesis may be correct; and so on.

A rapid decline of contaminant concentrations after very brief periods of pumping, as shown in Pattern II, should alert investigators to the very real possibility of internal contamination of the well—such as might occur from a poor surface seal, use of lubricating agents, or leaching of contaminants from the use of certain materials in construction of the well. As the well receives more and more uncontaminated waters from the aquifer, the concentrations of contaminants decline for each of the hypotheses just advanced. Again, supplemental data (here, regarding well construction) would be of great value in reducing the number of hypotheses which must be seriously considered.

Patterns III and IV appear to suggest not only the possibility of relatively brief encounters with recharge sources at some finite distance from a well which penetrates a contaminant plume, but also the possibility of intermittent loadings of contaminants—as might occur in fractured crystalline rock aquifers, karstic limestone aquifers and un-

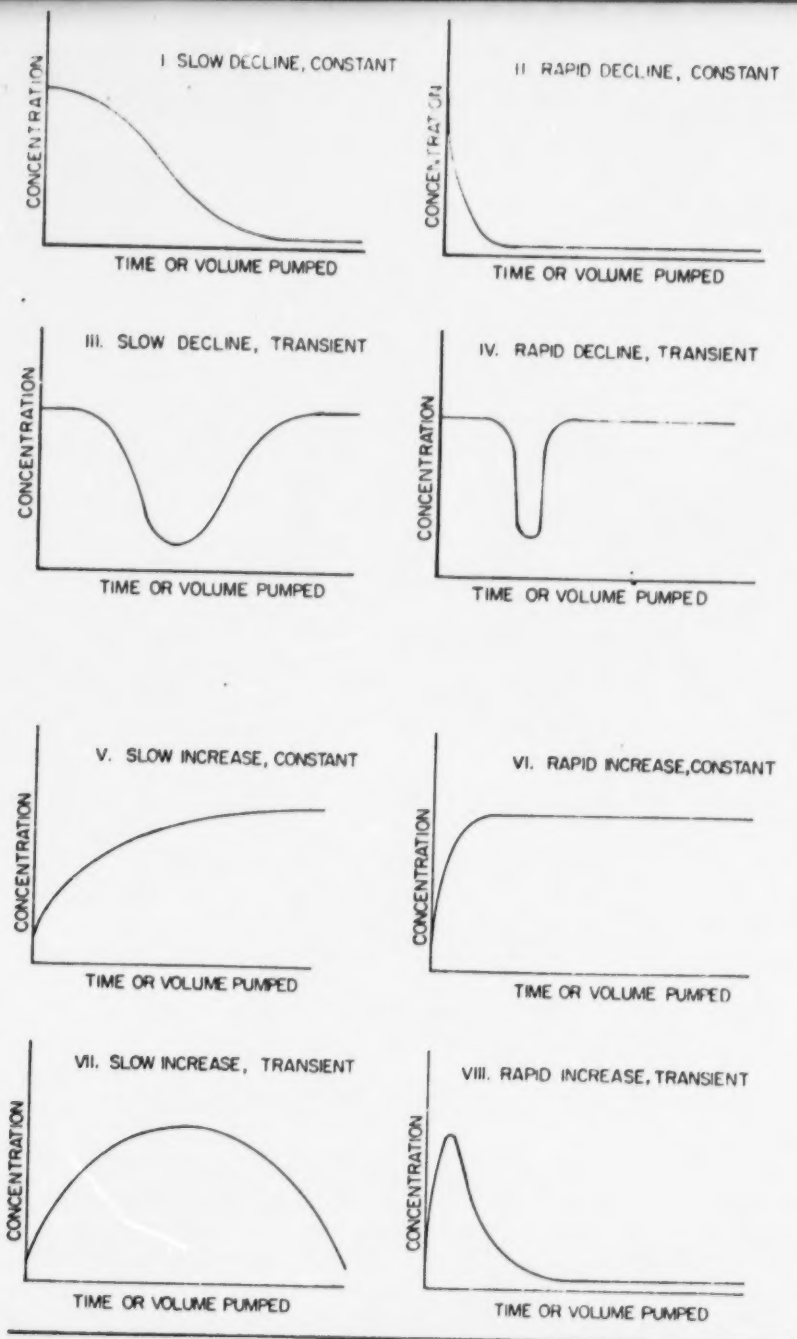

Figure 2. Hypothetical patterns of contaminant arrival

consolidated aquifers laced with large macropores. The more compressed the transient decline, the greater the tendency to dismiss it as a relatively unimportant anomaly. The more gradual the transient decline, the more credence that could be given to a local recharge effect. Once more, supplemental data would be of great benefit; if it can be demonstrated that a local stream provides recharge when a well is pumped, the induced recharge may well be a suitable explanation for a slow, transient decline.

Increasing trends of contaminant concentrations with continued pumpage, as illustrated by Patterns V through VIII (Figure 2) are also quite possible. A source of contaminants completely external to the well might explain Pattern V. The well would produce increasing concentrations of contaminants as it pulled greater volumes of the contaminant plume into it. Samples from nearby wells would be quite useful in verifying this hypothesis—both by levels of contaminants encountered, and, in the case of nearby pumping wells, by the ability to affect contaminant concentrations by creating hydraulic divides through well interference.

Pattern VI, though similar in most respects to Pattern V, would be more apt to result from physical, chemical or biological degradation of contaminants in the well itself—such as the loss of iron by precipitation from stagnant waters in casing storage, reported by Gibb and others (1981). The contaminant concentrations would rise rapidly as pumping continued because the stagnant, affected waters in casing storage would be quickly voided and replaced by waters from the surrounding formation.

The implications of Patterns VII and VIII are that some isolated plume is being sampled. The form of isolation may be as simple as physical occlusion by clay strata or intermittent release of the contaminants into the subsurface, or it may be a matter of relative contributions of recharge sources of uncontaminated waters versus the contaminant plume. As a final note, Pattern VIII may be the result of a combination of casing storage effects and poor well construction (leaky surface seal) or poor isolation of the aquifer of interest (communication of contaminated waters along the outside of the casing due to poor grouting). Supplemental data are, of course, essential to the interpretation of these patterns.

Distance of Draw Estimates

A simple approach to prediction of the arrival of a chemical contaminant from a known or selected distance to a well in response to pumpage involves the relationship of the total volume of water pumped at any time to the distance from which it came. Warner and Lehr (1977) have presented the elements of this approach for injection wells; it is extended here for pumping wells.

For example, suppose a well has been pumping for 100 minutes at a steady rate of 500 gallons per minute. The total volume of water pumped is 50,000 gallons or 6,684 cubic feet of water. Assuming that the well pulled water radially into the well, the 50,000 gallons or 6,684 cubic feet of water pumped out of the aquifer must have occupied a cylindrically shaped volume of the aquifer, centered on the well. The pumped waters were contained within the pores of the aquifer, with the remainder of the aquifer being

formation materials and retained waters; so the volume of the aquifer which held 6,684 cubic feet of water must, itself, be much greater than 6,684 cubic feet (Figure 3).

Given an estimate of the effective porosity, it is easy to calculate the aquifer volume that contained the 6,684 cubic feet of water pumped. Assuming the effective porosity of the aquifer in this example to be 0.20, the 6,684 cubic feet of water pumped were withdrawn from 33,420 cubic feet of aquifer volume.

To calculate the distance to the well from which the last few drops of water came, use the formula for the volume of a cylinder; $V = \pi r^2 h$, where V is the volume of the cylinder, r is the radial distance from the central axis of the cylinder to the outer surface of the cylinder, and h is the height of the cylinder (Figure 3). To solve for r, V and h must be known. V = 33,420 cubic feet of aquifer material, but h must be estimated from drillers records or other pertinent information regarding the effective thickness of the aquifer.

Assume the effective thickness of the aquifer in this example to be 50 feet. The wells may actually draw on a much greater thickness of saturated formations but several low permeability strata may occupy portions of that thickness; hence, it is important to distinguish between the "effective" aquifer thickness and the nominal thickness of the zone(s) of saturation available to the wells.

Solving for r, where V = 33,420 cubic feet and h = 50 feet, r = 14.59 feet. Hence, given ideal radial conditions and the assumptions invoked here regarding effective porosity and aquifer thickness, the last few drops of water produced after 100 minutes of pumping 500 gallons per minute were drawn into the well from a distance of about 15 feet. Similarly, any chemical contaminants in those waters also would have come from that distance (for convenience this will be assumed here, but it should be noted that many chemical contaminants do not move with the water; they may be retarded or attenuated, by various reactions with the aquifer materials or other contaminants).

Obviously, the power of this approach lies in its inherent simplicity. The investigator is able to make a rough correlation of the arrival time of contaminants at a well with the distance from which they were drawn. Table 1 contains estimates of radial distances of draw into a hypothetical well pumping at a constant rate of 500 gallons per minute from aquifers of various effective thicknesses and porosities, for specific durations. Figure 4 is a graphical representation of those same hypothetical data.

The bottom line of comparing the effects of various assumptions is that if either the effective porosity estimate or the effective aquifer thickness estimate is assumed to be smaller than the example just presented, then the calculated radial distance of draw is greater than in that example. Conversely, if either the effective porosity estimate or the effective aquifer thickness estimate is assumed to be greater, then the calculated radial distance is smaller. These relationships are quite sensible since, for example, a "tighter" aquifer (lower effective porosity)

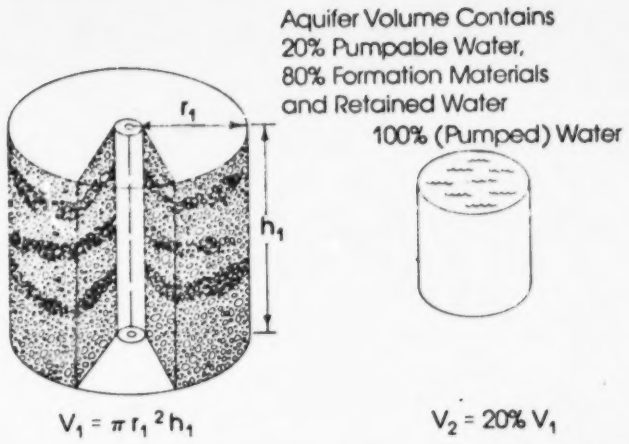

Figure 3. Comparison of volume of aquifer affected with volume of pumped water

Table 1. Total Volumes of Pumped Waters and Their Corresponding Radial Distances of Draw Into a Hypothetical Well for Select Durations of Constant Pumpage

Pumpage Duration (Minutes)	Volume Pumped (Gallons)	Volume Pumped (Cubic Feet)	Radial Distance of Draw (feet)		
			Case A	Case B	Case C
1	5.0×10^2	67	2.1	1.5	1.0
5	2.5×10^3	3.3×10^2	4.6	3.3	2.3
10	5.0×10^3	6.7×10^2	6.5	4.6	3.3
30	1.5×10^4	2.0×10^3	11	8.0	5.6
60	3.0×10^4	4.0×10^3	16	11	8.0
180	9.0×10^4	1.2×10^4	28	20	14
300	1.5×10^5	2.0×10^4	36	25	18

The hypothetical well is pumped at a constant 500 gallons per minute. The volume pumped is given in both gallons and cubic feet for convenience. Liters = 3.78 x gallons. Cubic meters = 0.028 x cubic feet. Meters = 0.31 x feet.

Radial Distance Case A assumes the effective aquifer thickness to be 25 feet and the effective porosity to be 0.20 (which has the same effect on the radial distance calculation as assuming the effective aquifer thickness to be 50 feet and the effective porosity to be 0.10).

Radial Distance Case B assumes the effective aquifer thickness to be 50 feet and the effective porosity to be 0.20 (Case B is the example discussed in the text).

Radial Distance Case C assumes the effective aquifer thickness to be 100 feet and the effective porosity to be 0.20 (which has the same effect on the radial distance calculation as assuming the effective aquifer thickness to be 50 feet and the effective porosity to be 0.40).

These radial distance of draw calculations assume that the pumped waters were withdrawn from a cylindrically shaped volume of aquifer material which is axially centered on the well bore.

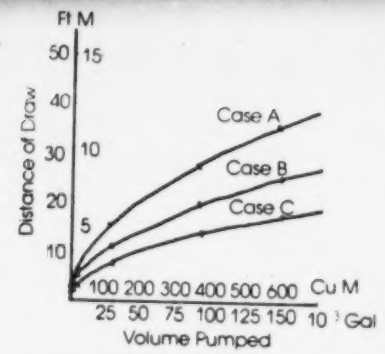

Figure 4. Radial distance of draw for a well with a constant discharge of 500 gpm (see Table 1 notes)

would need a greater total volume to contain the same pumped waters; which, in turn, would lead to a greater calculated radial distance of draw. Note also, that a large pumping rate is not necessary to produce large distances of draw; a five gallon per minute pumping rate from an aquifer with an effective porosity of 0.002 will result in the same distance of draw estimates as a 500 gallon per minute pumping rate from an aquifer with an effective porosty of 0.20 (e.g., Table 1).

It is useful to examine how this approach can be adapted to solve for the distance from which a contaminant came when considerable aquifer anisotropy and nonhomogeneity must be taken into account. Aquifers which are comprised of several strata of differing permeabilities invariably suffer from anisotropy and nonhomogeneity. For example, the tremendous differences in effective porosity and hydraulic conductivity which result from depositional stratification of stream and glacial gravel and tight clay, till and silt, give rise to the widely known nonhomogeneity and anisotropic flow of glacial aquifers (Williams and Farvolden 1969 and Hendry 1982). If waters cannot easily flow through a layer, then they will flow around, over or under that layer. Special precautions must, therefore, be taken to interpret flow directions based on water level measurements in such aquifers; the flow directions will not be perpendicular to water level contours (Fetter 1981; Baker and Herbert 1982). The chemical contaminants may thus be carried through a rather tortuous path, often never reaching isolated pockets of an aquifer or traveling farther than expected.

Distance of draw calculations can be easily adapted to various situations involving aquifer anisotropy and nonhomogeneity by changing assumptions about the geometry of the aquifer volume which held the pumped waters. For example, an aquifer zone which has exhibited a marked degree of anisotropy and nonhomogeneity in a single predominant direction can be assumed to limit the source of waters drawn into the well to a rectangular aquifer volume oriented along that predominant direction, rather than to a cylindrical aquifer volume.

Calculations for a rectangular case which asumes that a well draws water from a portion of the aquifer that closely resembles a rectangular box whose length is twice as great as its width are presented in Table 2. The formula for the aquifer volume is given by $V = 2\ w^2h$ where V is again the volume of aquifer material which contained the pumped waters, w is the width of the rectangular box, and 2w is equal to the length of the box and h is again the effective aquifer thickness. It is easy to solve for w, the box width, and just as easy to multiply by two for the box length to obtain the surface dimensions of the aquifer volume which held the pumped waters. If it is assumed that the well is perfectly centered in this surface area, then the last few drops of water pumped from the well could have come from as far away as one-half of the length of the box (ignoring diagonals) or from as near as one-half of the width of the box (Figure 5).

Table 2 is a tabulation of such maximum and minimum distances for a well pumping at 500 gallons per minute. Figure 6 is a graphical representation of the data in Table

Table 2
Total Volumes of Pumped Waters and Their Correspondence "2 : 1 Rectangle" Distances of Draw Into a Hypothetical Well for Select Durations of Constant Pumpage

Pumpage Duration (Minutes)	Volume Pumped (Gallons)	Volume Pumped (Cubic Feet)	Maximum:Minimum Distances of Draw (feet		
			Case A	Case B	Case C
1	5.0×10^2	67	2.6 : 1.3	1.8 : 0.9	1.3 : 0.7
5	2.5×10^3	3.3×10^2	5.8 :2.9	4.1 : 2.0	2.9 : 1.4
10	5.0×10^4	6.7×10^2	8.2 : 4.1	5.8 : 2.9	4.1 : 2.0
30	1.5×10^4	2.0×10^3	14 : 7.1	10 : 5.0	7.1 : 3.5
60	3.0×10^4	4.0×10^3	20 : 10	14 : 7.1	10 : 5.0
180	9.0×10^4	1.2×10^4	35 : 17	24 : 12	17 : 9
300	1.5×10^5	2.0×10^4	45 : 22	32 : 16	22 : 11

The hypothetical well is pumped at 500 gallons per minute. The volume pumped is given in both gallons and cubic feet for convenience. Liters = 3.78 x gallons. Cubic meters = 0.028 x cubic feet. Meters = 0.31 x feet.

Case A assumes the effective aquifer thickness to be 25 feet and the effective porosity to be 0.20 (which has the same effect on the distance calculations as assuming the effective aquifer thickness to be 50 feet and the effective porosity to be 0.10).

Case B assumes the effective aquifer thickness to be 50 feet and the effective porosity to be 0.20 (Case B is the example discussed in the text).

Case C assumes the effective aquifer thickness to be 100 feet and the effective porosity to be 0.20 (which has the same effect on the distance calculations as assuming the effective aquifer thickness to be 50 feet and the effective porosity to be 0.40).

These distance of draw calculations assume that the pumped waters were withdrawn from a rectangular box-shaped volume of aquifer material which is horizontally centered on the wellbore. The depth of the rectangular box is equal to the assumed effective aquifer thickness. The length of the rectangular box is equal to twice its width. The "maximum" distance of draw is equal to half the length of the rectangular box and the "minimum" distance of draw is equal to half the width of the rectangular box (diagonal distances are comprised of length and width components, and are not considered—despite the fact that diagonal distances do exceed "maximum" distances as defined here).

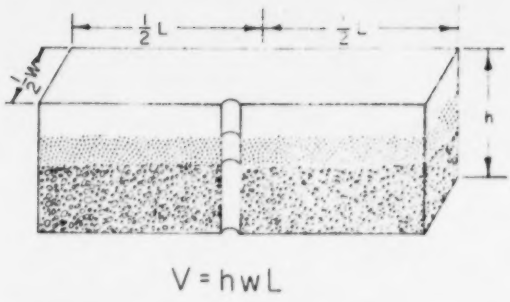

Figure 5. Conceptual representation of 2:1 anisotropic distance of draw

2. Table 2 and Figure 6 also include additional data and curves which illustrate the effects of reducing and increasing the effective porosity or effective aquifer thickness estimates.

It is also not unreasonable to take a hybrid approach, wherein the initial pumping intervals are assumed to fit the ideal radial well draw approach and later pumping intervals are assumed to fit a rectangular well draw approach. Such hybrid approaches would be particularly applicable in situations where hydrologic flow boundaries occur at some known distance from the well.

Statistical Considerations

Figures 7 and 8 illustrate the aquifer zones bounded by the various radial and rectangular distances for the data given in Tables 1 and 2, respectively. Note that a conventional bailed sample would be equivalent to a zero minutes sample, i.e., it would represent an area no greater than the nominal size of the well casing. A pumped sample has a much greater chance of providing detailed information on the aquifer water quality, as opposed to a static sample.

The surface area represented by a 2-inch diameter monitoring well is equal to $\pi r^2 = 3.14$ square inches or 0.0218 square feet. Three monitoring wells per acre (a fairly high density) thus nominally represent 0.0654 square feet per acre. This amounts to less than 0.0002 percent of the surface area of that acre. With adherence to the recommended purging of stagnant waters from the monitoring wells, it is likely that each monitoring well could represent as much as 10-times its nominal surface area; but 0.002 percent of an acre still constitutes a statistically insignificant representation. To compound the problem, considerable aquifer anisotropy and heterogeneity can be reasonably assumed so that placement of the monitoring wells to ensure interception of contaminants is extremely difficult. This is why adequate representation of aquifer quality, and adequate physical descriptions based on drilling logs from monitoring wells, are so difficult to achieve.

Now assume that one pumping well and two monitoring/observation wells are available per acre. Pumping tests will considerably strengthen attempts to physically describe the aquifer, and pumped samples will represent greater volumes (and surface areas) of the aquifer. Further assume that the aquifer has an effective porosity of 0.20 and an effective thickness of 50 feet, and that the pumping well discharges 500 gallons per minute for 100 minutes, as per the example used in the distance of draw discussions.

Again, the 50,000 gallons pumped were drained from 33,422 cubic feet of the aquifer. Dividing by the effective thickness, this means

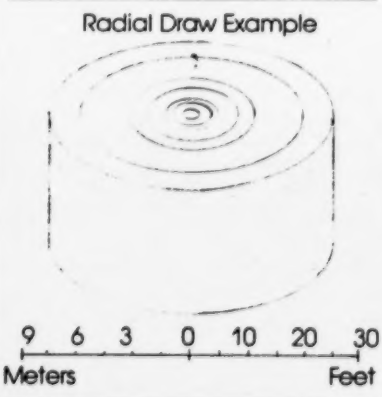

Figure 7. Aquifer zones bounded by radial distances of draw for select durations of constant pumpage (see Table 1 data and notes)

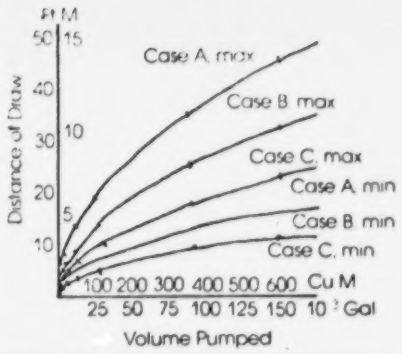

Figure 6. 2:1 Rectangle distance of draw into a well of constant discharge of 500 gpm (see Table 2 notes)

that the average composition of those drained waters represents 668 square feet of the aquifer surface area. Now the percentage of an acre of aquifer surface area represented is 1.53 percent—far more statistically significant than the 0.0002 percent contributed by each monitoring well. At 300 minutes of pumping, the percentage rises to 4.60—a very respectable value. Table 3 gives the results for several additional calculations of this kind so that direct comparison of the distance of draw estimates in Tables 1 and 2 may be made with the aquifer surface areas (and percentages of an acre) represented by them.

Casing Storage Effects

In discussing the testing of a well of large diameter, Papadopulos and Cooper (1967) describe the following method to estimate the duration during which stagnant waters standing in the well (casing storage)

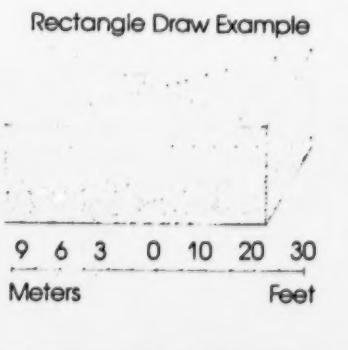

Figure 8. Aquifer zones bounded by 2:1 rectangle distances of draw for select durations of constant pumpage (see Table 2 data and notes)

are drawn on by pumping:

$$t_c = \frac{1.440\,(r_c^2 - r_p^2)}{T}, \text{ where}$$

t_c is the time during which waters in casing storage can contribute to pumped waters (minutes),

r_c is the internal radius of the well casing (feet),

r_p is the external radius of the pump column/discharge tubing (feet), and

T is the transmissivity (cubic feet per day per foot, or square feet per day).

Using this equation, examples have been calculated for three hypothetical wells, under a variety of assumed transmissivities. The resulting t_c estimates are listed in Table 4. As can be seen by Example 1 in Table 4, typical high yield public water supply wells in moderate to highly transmissive aquifers would draw water exclusively from the aquifer after very brief periods of contributions of water from casing storage. Similarly, Examples 2 and 3 in Table 4 show that this would also be true of fairly small pumping wells capable of producing only a few gallons per minute.

Several implications of these hypothetical examples are apparent. Calculations of distance-of-draw estimates need not be viewed with suspicion because of casing storage effects, since errors introduced by assuming that all pumped waters come from the aquifer will be insignificant after very brief periods of pumpage. Stagnant waters residing in the well casing will provide only short-lived water quality anomalies. Gibb and others (1981) showed this to be true even for relatively low transmissivity aquifers sampled by very low volume sampling devices.

Scalf and others (1981) note that adequate purging of stagnant waters prior to sampling with bailers and other low volume sampling devices is a necessity. Data from wells which have not been identically purged of stagnant waters are not comparable; use of such data to construct concentration contours (for several wells sampled during a single survey) or historical trends (for a single well sampled at different times) is invalid and misleading. The same logic must be applied to data generated from wells which have been sampled after much longer, but dissimilar, durations of pumpage; those data are not directly comparable and their use, too, may result in erroneous conclusions regarding patterns of contaminant concentrations.

Geohydraulic Concerns

Some comments regarding the relationship between the distance from which waters were drawn into a well, and that portion of the aquifer influenced by the cone of depression of a pumping well are in order. Figure 9 illustrates the cone of depression caused by the pumping of water from an ideal aquifer; several possibilities exist for the related distance from which waters were drawn, and these are also incorporated into Figure 9. The important points of Figure 9 are: (1) the rate of duration of pumpage and the aquifer characteristics determine the shape and position of the cone of depressed water levels surrounding the well, (2) the shape and position of the cone stabilize rapidly in highly transmissive aquifers and slowly in aquifers with very low transmissivity, and (3) the distance from which aquifer waters are drawn is almost exclusively dependent on the total volume of water pumped at any given time.

"Almost exclusively" implies some limiting factor to the relationship between the distance from which aquifer waters were drawn and the total volume of pumped waters. That arises from the fact that there is indeed a *practical* limiting distance to the pressure influence and cone of depressed water levels surrounding a well.

As the volume of pumped waters expands to the edge, and then beyond the practical limits of the

Table 3. Total Volumes of Pumped Waters and Their Corresponding Aquifer Surface Areas Represented for Select Durations of Constant Pumpage by a Hypothetical Well

Pumpage Duration (Minutes)	Volume Pumped (Gallons)	Volume Pumped (Cubic Feet)	Aquifer Surface Area Represented (square feet) and Equivalent Percentages of One Acre (in parentheses)		
			Case A	Case B	Case C
1	5×10^2	67	13 (0.03%)	6.7 (0.02%)	3.3 (0.01%)
5	2.5×10^3	3.3×10^2	67 (0.15%)	33 (0.08%)	17 (0.04%)
10	5.0×10^3	6.7×10^2	1.3×10^2 (0.31%)	67 (0.15%)	33 (0.08%)
30	1.5×10^4	2.0×10^3	4.0×10^2 (0.92%)	2.0×10^2 (0.46%)	1.0×10^2 (0.23%)
60	3.0×10^4	4.0×10^3	8.0×10^2 (1.8%)	4.0×10^2 (0.92%)	2.0×10^2 (0.46%)
180	9.0×10^4	1.2×10^4	2.4×10^3 (5.5%)	1.2×10^3 (2.8%)	6.0×10^2 (1.4%)
300	1.5×10^5	2.0×10^4	4.0×10^3 (9.2%)	2.0×10^3 (4.6%)	1.0×10^3 (2.3%)

The hypothetical well is pumped at a constant 500 gallons per minute. The volume pumped is given in both gallons and cubic feet for convenience. Liters = 3.78 x gallons. Cubic meters = 0.028 x cubic feet. Meters = 0.31 x feet.

Case A assumes the effective aquifer thickness to be 25 feet and the effective porosity to be 0.20 (which has the same effect on the calculations of aquifer surface area represented as assuming the effective aquifer thickness to be 50 feet and the effective porosity to be 0.10).

Case B assumes the effective aquifer thickness to be 50 feet and the effective porosity to be 0.20 (Case B is the example discussed in the text.)

Case C assumes the effective aquifer thickness to be 100 feet and the effective porosity to be 0.20 (which has the same effect on the calculation of aquifer surface area represented as assuming the effective aquifer thickness to be 50 feet and the effective porosity to be 0.40).

These calculations of aquifer surface area represented are independent of assumptions regarding the geometric shape of the volume of aquifer material from which the pumped waters were withdrawn.

Table 4. Estimates of Durations of Casing Storage Effects for Three Hypothetical Wells

Example 1. A hypothetical well having an inside diameter of 12 inches (r_c = 0.5 feet) and a pump column outside diameter of 6 inches (r_p = 0.25 feet).

Transmissivity, T (square feet/day)	Duration of Casing Storage Effects, t_c (minutes)
10^2	2.7
10^3	2.7×10^{-1}
10^4	2.7×10^{-2}
10^5	2.7×10^{-3}

Example 2. A hypothetical well having an inside diameter of 6 inches (r_c = 0.25 feet) and a pump column outside diameter of 4 inches (r_p = 0.167 feet).

Transmissivity, T (square feet/day)	Duration of Casing Storage Effects, t_c (minutes)
10^2	5.0×10^{-1}
10^3	5.0×10^{-2}
10^4	5.0×10^{-3}
10^5	5.0×10^{-4}

Example 3. A hypothetical well having an inside diameter of 2 inches (r_c = 0.027 feet) and a pump column outside diameter of 1 inch (r_p = 0.0069 feet).

Transmissivity, T (square feet/day)	Duration of Casing Storage Effects, t_c (minutes)
10^2	3.0×10^{-1}
10^3	3.0×10^{-2}
10^4	3.0×10^{-3}
10^5	3.0×10^{-4}

These estimates were produced by the method presented by Papadopulos and Cooper (1967). Centimeters = 2.54 x inches. Meters = 0.31 x feet. Square meters = 0.093 x square feet.

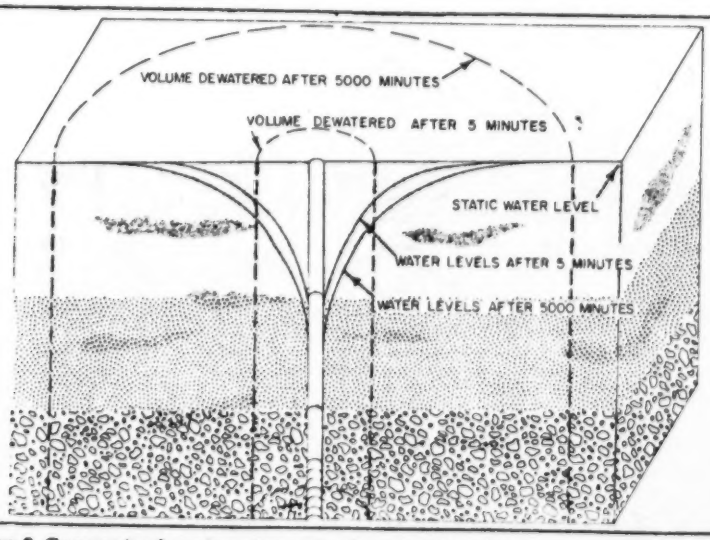
VOLUME DEWATERED AFTER 5000 MINUTES
VOLUME DEWATERED AFTER 5 MINUTES
STATIC WATER LEVEL
WATER LEVELS AFTER 5 MINUTES
WATER LEVELS AFTER 5000 MINUTES

Figure 9. Conceptual comparison of volumes of aquifer pumped with cones of depression for select durations of constant pumpage

cone of depression, the produced well waters are primarily comprised of waters which were upgradient of the well and have recently made their way in to replace the waters pumped out by the well. The distance at which this can first occur is where the depression caused by pumping of the well is exactly countered by the natural gradient.

Put another way, the "distance of draw to total volume pumped" relationship is valid only until that distance reaches the point where the cone of depression fades into the natural gradient. At that point, the well must wait for a refill of upgradient waters (of course, the wait is imaginary, since upgradient waters are continuously moving toward the well). After that practical limit has been reached, conclusions regarding distances of draw can be made only for the upgradient direction which is contributing the vast majority of the waters now taken into the well. In such a case, the distance of draw for the upgradient waters could be estimated by assuming a rectangular strip of upgradient waters with a width equal to the practical limits/effective diameter of the cone of depression. The length of the strip would, of course, equal the distance from which upgradient waters were drawn/had flowed to the well.

Other important characteristics affecting the movement of contaminants in response to hydraulic stresses in aquifers are the molecular diffusion and bulk mechanical components of hydrodynamic dispersion and natural hydraulic gradients. The molecular diffusion component of hydrodynamic dispersion is important in determining the spread of contaminants in very low transmissivity aquifers, where it dominates over the bulk mechanical dispersive effects. In low transmissivity aquifers, contaminants may migrate considerably upgradient or cross-gradient with respect to the local flow regime; whereas this is rarely the case of high transmissivity aquifers (dense contaminants are an important exception).

Low hydraulic gradients associated with highly transmissive aquifers tend to limit the effects of hydraulic/mechanical dispersion on the movement of contaminants. This is because the mechanical mixing (or dispersion) of contaminated waters into unaffected waters, caused by flow around, under or over semipermeable and impermeable materials, is much more

pronounced when the available driving force is increased.

Distance of draw estimates are also affected by the manner in which water (and contaminants) move through the unsaturated zone. Contaminant transport by downward percolation from the surface, through intervening unsaturated semipermeable and permeable strata to ground water can be expected to be retarded and redirected laterally. Dependent on the direction of lateral travel, a nearby source of contaminants may have an immediate and serious effect on a well or it may have little or no effect on the well. Of course, the magnitude of lateral travel is extremely important in this regard. This effect is often fairly minor (tens of feet of lateral migration). Due to the rapidly changing characteristics of the glacial, fluvial and alluvial material comprising many aquifers (e.g., discontinuities in the clays), hundreds or thousands of feet of horizontally continuous tight clays or silts are generally rare. Vertical variations are often more exaggerated; stratum thicknesses of inches to a few tens of feet are common.

As a natural consequence of these relatively unresolvable uncertainties, highly accurate distance of draw estimates may be difficult to produce. Therefore, it would be unwise to exclude potential contamination sources from further investigation simply because their physical surface boundaries lie 50 feet, 100 feet or more beyond the distance of draw calculated for a given contaminant by the methods described here. Numerous uncertainties are involved; the roles that heavy pumping, anisotropy, nonhomogeneity and hydrodynamic dispersion play in redistributing contaminants throughout the aquifer have been addressed already. A few other uncertainties deserving of mention, however, are the role precipitation plays in determining the concentration of contaminants reaching the aquifer by leaching slugs of contaminants from surface sources on a sporadic basis, the roles of physiochemical processes (sorption, ion-exchange, precipitation etc.) in attenuating/ retarding contaminant movement and the role of biota in transforming or degrading contaminants. These latter uncertainties may have serious consequences if ignored entirely, though their effects may not need to be quantified rigorously (indeed, it may not be possible to do so).

Even if one cannot be sure that the concentrations determined are greater or less than the average concentration of the contaminant plume, one may validly interpret relative arrival times, similarities of contaminant identities, relative concentration ratios and so on. Again, the most serious consequence of excluding uncertainties from contaminant transport considerations is that it will unduly restrict future investigations and conclusions as to potential sources and fates/ migrations of the contaminants.

Summary

When drawdown measurements are taken in conjunction with chemical time-series samples, a combined data set results which adequately describes the spatial variability of the contaminants and the aquifer transmissivity and storage values. This is exactly the kind of information specified by Pfannkuch (1981), among many others, as essential to the efficient design of proper monitoring systems and remedial actions.

The noncomparability of raw data collected by point-sampling wells or sampling discharging wells of different flow rates, pumping durations and/or construction is easily demonstrated by simple statistical comparisons. The technique described here lends insights into data transformations (e.g., direct weighting by volume of aquifer sampled) potentially useful for valid comparisons of such data. Further implications of the method include the ability of the user to define minimum purging requirements and sampling radii of monitoring wells, and the need for sampling by methods which create an appreciable local gradient toward the well.

Incorporation of the suggestions of Pettyjohn (1982) regarding the need for seasonal appraisals of contaminated sites subject to significant recharge periods rounds out the overall approach appropriate for investigation of the vast majority of hazardous waste sites, surface impoundments, landfills, spills and the like. In essence, crossing some of the new frontiers in ground-water research described by Keeley (1982) may simply involve making the most of classical geohydraulic testing and arithmatic calculations. It is the opinion of this author that chemical time-series sampling, like adequate aquifer testing, is a necessary technique for valid ground-water contamination investigations.

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Disclaimer

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Biographical Sketch

Joseph F. Keely received his B.S. in professional chemistry (1975) and his M.S. in hydrology (1979) from the University of Idaho. He has served as senior laboratory scientist for the Idaho Bureau of Mines and Geology (1977-80) and as hydrologist for the U.S. EPA Region 10's Drinking Water Programs Branch (1980-81). He now holds the position of hydrologist with the Ground Water Research Branch at EPA's Robert S. Kerr Environmental Research Laboratory, where his efforts are directed toward geohydraulic and hydrogeochemical investigations of ground-water contamination incidents, coordination of groundwater modeling research and instructional assistance.